COMPACT, LOW-POWER ATOMIC TIME AND FREQUENCY STANDARDS

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ABSTRACT

We report the status of ongoing activities in development of a compact, low-power atomic time/frequency standard, the Chip-Scale Atomic Clock (CSAC). The status of efforts addressing the refinement of the CSAC for improved mechanical and environmental robustness is described. The improved frequency stability offered by CSAC has the potential to impact a number of system applications, and these impacts are discussed.

1. INTRODUCTION

Time and frequency standards are key elements of many DoD communications, navigation, networking and sensing systems. In many cases, the performance of the standard may be a limiting factor that defines key performance characteristics of the system. Quartz crystal-based frequency standards are widely used due to their excellent short-term frequency stability, compact size and low power consumption, although they are typically limited with respect to long-term frequency stability. By contrast, atomic time and frequency standards provide outstanding long-term stability, but their large size and high power consumption typically preclude use in compact or portable system applications. The availability of a compact, low-power frequency standard providing the long-term frequency stability characteristic of an atomic clock with a size and power consumption comparable to present-day TCXO crystal-based components would enable dramatic improvements in frequency stability for a wide range of DoD communications and navigation systems. This critical need is presently being addressed under the Chip-Scale Atomic Clock (CSAC) program sponsored by the Defense Advanced Research Projects Agency (DARPA). Under this program, we have demonstrated the technologies necessary to achieve a component size less than 1 cm^3, power consumption below 30 mW, and short-term frequency stability characterized by an Allan Deviation better than $1x10^{-11}$ (at 1hr integration time).

A brief background on the CSAC is provided below. Additional details on the components and construction may be found in (DeNatale et al., 2008).

A number of different physical processes and system architectures can be used to create an atomic frequency reference. The baseline approach used for the CSAC has been Coherent Population Trapping (CPT) (Stahler, 2002; Kitching, 2001; Kitching, 2005). In this technique, two coherent optical signals are incident upon an atomic vapor sample. Each of the beams is tuned to the optical excitation energy for one of the two hyperfine ground states. Under this condition, a quantum coherence between the two hyperfine components will be generated creating a state that does not interact with the optical fields and for which the transition probabilities are sharply reduced. In this "dark state," optical absorption sharply decreases and transmission through the cell increases. The CPT effect can also be generated with a single optical source modulated at microwave frequencies. If the optical frequency is the average of the excited state transition frequencies for the hyperfine ground states and the microwave modulation frequency is half the hyperfine splitting frequency, the modulation sidebands will create the two optical fields necessary for CPT generation. By monitoring cell transmission as a function of microwave tuning, a sharp transmission maximum will be observed at this modulation frequency condition, and provide the stable frequency reference.

A schematic architecture of the CPT-based CSAC is shown in Fig. 1. A 795nm VCSEL tuned to the D1 transition of Rb^{87} is RF modulated to create the proper optical fields. This is passed through beam conditioning optics and through a vapor cell containing Rb87 and controlled pressure of buffer gas. The transmitted light is detected by a photodetector that is used to monitor the creation of the microwave resonance of the CPT operation. Electronic control loops are used to lock the modulation frequency to this resonant signal and stabilize the VCSEL wavelength.

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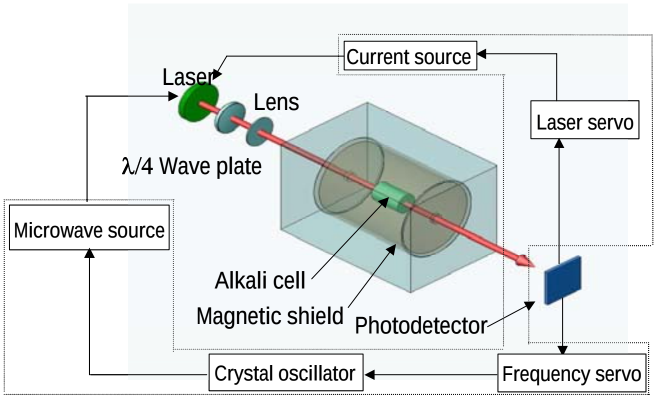

Fig. 1: Schematic of Coherent Population Trapping architecture used in CSAC

As described in (DeNatale et al., 2008), these components have been developed, miniaturized, and assembled into a compact, low-power form factor compliant with the aggressive program goals of 1cc volume, Fig. 2, 30mW power, and fractional frequency instability (Allan Deviation) below 1×10^{-11} (τ=1hr), validating the feasibility of a high-stability time/ frequency standard.

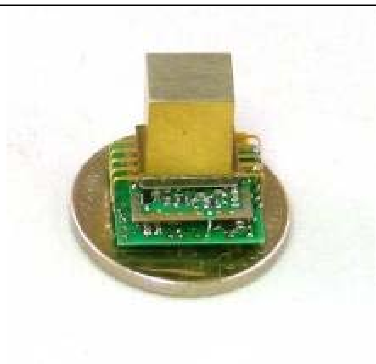

Fig.2: Compact CSAC assembly demonstrated in DARPA Phase-III CSAC Program.

2. PRESENT DEVELOPMENT ACTIVITIES

2.2 CSAC Refinement

The Phase-III CSAC development efforts successfully demonstrated the capability of the CSAC technology to achieve aggressive levels of size and power reduction while maintaining a high degree of frequency stability. Under the ongoing Phase-IV program, we are building upon these accomplishments to advance the CSAC maturity and facilitate its use in fielded system applications. A key element of this will be to demonstrate and validate the compatibility of the CSAC with the functionality, reliability, and environmental robustness needed for system use. This will promote user acceptance and enable the system developers to exploit the unique capabilities CSAC offers. Elements of the CSAC refinement include:

Ruggedization – The previous CSAC demonstration modules were designed to demonstrate the compatibility of the technology with the low-power, compact size goals of the program. Limited consideration was given to mechanical and environmental robustness in these earlier builds. For fielded system applications, however, the devices must be able to reliably withstand the harsh environments of operational use.

Present activities are addressing refinement of the CSAC construction for increased robustness under environmental stresses (in particular temperature, shock and vibration). With respect to the micromachined physics package, design modifications have incorporated reinforced mechanical interfaces at load-bearing joints, shock-resistant thermal isolation tethers, and high-reliability vacuum package sealing.

With respect to the control electronics, circuit design and construction are leveraging the extensive experience of Rockwell Collins, Inc. (RCI), in the design, production and testing of high-performance fielded quartz crystal-based frequency standards. CSAC incorporates numerous features from the RCI Time Compensated Crystal Oscillator (TCCO) frequency standard. This high-performance product, used extensively in airborne radios (such as the ARC-210), meets extremely challenging environmental specifications (-55C to +105C operating temperature range). The TCCO reliability has been validated through the fielding of in excess of 70,000 units. Elements of the TCCO architecture have been incorporated into the new CSAC control electronics to improve operation over a wide temperature range and high-stability, modulation-free frequency output.

The TCCO is digitally compensated crystal oscillator. The reference oscillator uses a low temperature hysteresis crystal, which is not compensated for temperature. The reference oscillator frequency is characterized over temperature and stored in a non-volatile memory. In the case of the TCCO this is a third overtone SC cut crystal with a Q well over two million. Since this crystal cannot be pulled to a nominal frequency, a second oscillator, which is a Voltage Controlled Crystal Oscillator (VCXO), is used to provide the frequency output. A micro-controller measures the VCXO frequency using the SC cut crystal as a reference and simultaneously measures the temperature of the SC cut crystal. The micro-controller then calculates the reference oscillator frequency using a look-up table with the reference crystal's temperature-frequency characteristics. With this information, the micro-controller then calculates the VCXO frequency error and corrects the output word to the digital to analog converter, which corrects the VCXO's frequency. The fundamental architecture of the CSAC control electronics is based on the RCI TCCO. This technique will be

utilized to extend the operational temperature range and overall robustness. One of the distinct advantages of this architecture is the low DC power consumption.

Streamlined Assembly – The previous CSAC demonstration units were hand-assembled by skilled engineers. For widespread system use, the CSAC assembly must migrate to a more streamlined manufacturing process to reduce high-cost touch labor and reduce unit-to-unit variability. The Phase-IV design refinements include improvements addressing these assembly processes. A modular assembly approach is being adopted that enables independent assembly and test of the optics module and alkali vapor cell module, respectively. These elements are then integrated into an operational physics package using keyed alignment features to facilitate placement, Fig. 3. This approach will also enable greater unit-to-unit repeatability and permit transition to standard multichip module (MCM) assembly environments.

Improved User Interface – The previous CSAC demonstration units had been specifically designed to achieve minimum power consumption. This required elimination of many of the user interface functions that facilitate system integration of the CSAC. In the earlier modules, the reference output was the 569MHz primary frequency from the VCXO with a low-frequency modulation superimposed. The refined CSAC is incorporating a clean, (unmodulated) 10MHz frequency output and 1PPS timing signal, compatible with standard user interfaces.

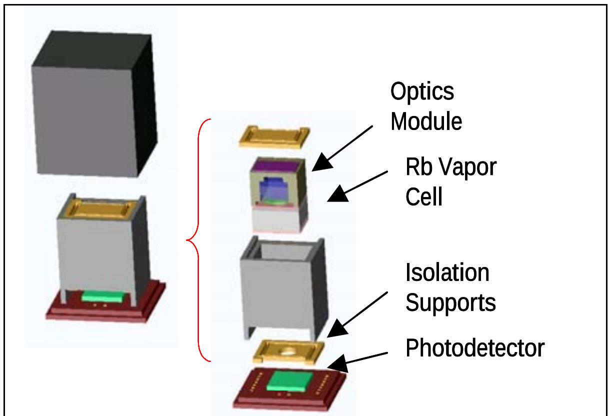

Fig. 3: Schematic of modular CSAC construction.

2.3 CSAC Environmental Testing

A key element in the insertion of CSAC into fielded military systems will be its compatibility with the accepted test procedures for military frequency standards. To establish this compatibility, we will be testing the refined CSAC prototypes for compliance with MIL-STD test protocols. This will leverage the comprehensive test infrastructure in place at Rockwell Collins in support of their crystal-based military frequency standard products used in GPS, radio and SATCOM systems. As a producer of DoD frequency standards, RCI primarily qualifies against two military standards: 1) MIL-STD-810F *"Environmental Engineering Considerations and Laboratory Tests"* and 2) MIL-STD-202G *"Test Method Standard for Electronic and Electrical Component Parts."*

The objective is to demonstrate the technical readiness level (TRL) of the CSAC frequency standard through testing in an operational environment and integration within a system (i.e., TRL 6). The environmental conditions that will be tested include: 1) temperature, 2) shock / vibration, 3) humidity and 4) magnetic field.

- Temperature: One of the critical parameters in any frequency standard is the operational stability over temperature. The CSAC unit will be characterized over a broad temperature range to assure transition to a large number of DoD platforms. The target operational temperature is -40°C to +75° C. Another critical parameter is frequency aging. The rate of change over time will be measured on an ongoing basis in order characterize the aging parameter. The objective is to demonstrate the capability of the CSAC to pass the MIL-STD environmental requirements, and thereby transition the technology to a DoD program of record or a future DoD development program. Temperature compensation algorithms will be used to minimize temperature variation. This will leverage extensively from technology presently in use for RCI crystal-based frequency standards.
- Shock / Vibration: Use of robust thermo-mechanical supports to suspend and thermally isolate the physics package will ensure survival under shock and high vibration environments. Finite element modeling and experimental test have shown the laser-cut Circlex supports designed in Phase-III capable of supporting greater than 2000g acceleration levels without failing (Laws et al., 2007). This is consistent with other reports of survival of CSAC devices with thin polymide tethers to 500g (Lutwak et al., 2007).
- Humidity: The CSAC physics package is sealed under vacuum, and not impacted by humid ambient. To ensure no issues with the circuit, a secondary hermetic enclosure around the physics package and circuit is used, Fig. 4. This will be backfilled with dry inert gas to ensure immunity to humid ambient. Testing will be performed to validate the immunity.
- Magnetic field: The CSAC requires magnetic shielding to preserve stable CPT operation. In the prototypes, the baseline approach is to use a two-layer shield. The primary shielding will be incorporated into the physics package vacuum

enclosure, with additional shielding provided by the outer enclosure.

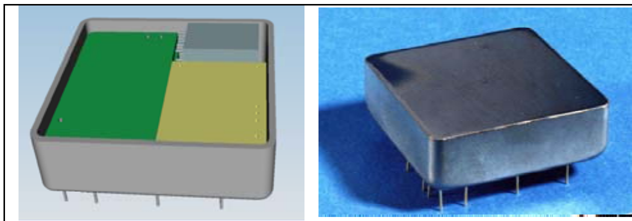

Fig. 4: Schematic and photograph of CSAC module assembly and packaging.

3. CSAC APPLICATIONS

The improved time and frequency stability offered by CSAC technology has the potential for significant impacts to a wide range of DoD systems. Examples of classes of systems that could potentially benefit from an improved time base include (Kenyon, 2008; Beard, 2002):

- GPS: The reduced aging of CSAC relative to quartz-based time standards could reduce the code search space and hence the reacquisition time for GPS receivers and enable direct Y-Code reception (Kenyon, 2008; Rollo, 2007). The improved timing can also improve jamming resistance, defense against spoofed signals, and reduce the number of satellites required for an accurate PNT solution (Kenyon, 2008; Rollo, 2007).
- SatCom: Portable satellite communication (SATCOM) systems can benefit from improved network acquisition via improved time uncertainty provided by the CSAC capability (Kenyon, 2008). The SATCOM systems involve transmission of secure TDMA waveforms that must be synchronized between satellite and terrestrial terminals. This time synchronization enables the terminal to hop to the correct frequency at the appropriate time. Without synchronization the terminal is blind, looking for information when it is not available and the satellite signal cannot be acquired. By incorporating the CSAC into the SATCOM terminal to preserve a precise time base in the absence of GPS, network acquisition time can be reduced substantially. It is estimated that by reducing the time uncertainty through the use of CSAC, the network acquisition time potentially can be improved >100X. In addition, the present use of ovenized crystal oscillators has consequences associated with warm-up time. This can be unacceptable in the network intensive battlefield, especially in dynamic environments involving rapid force movement, such as in comm-on-the-move, comm-on-the-halt, and comm-on-the-quickhalt operations. These CONOPS are becoming increasingly important considerations in system operation as well as operational tactics, and the faster warmup time of the CSAC can provide tangible benefits to the system operation.
- Networked Systems / Sensors: Timing and synchronization is a critical element of network management and operation of networked systems. The improved time base provided by CSAC can enable a number of novel network architectures with improved robustness and bandwidth relative to traditional approaches. Further, precision time tagging of events from distributed sensors enables improved localization and data processing.
- EW / IED Protection: High-energy electromagnetic jamming creates the risk of cosite interference with other RF communications, navigation, and sensing systems. Time synchronization of assets to coordinate T/R “windows” can be effective in avoiding self-jamming.
- Undersea Systems: The undersea environment is inherently GPS-denied, and a number of operational advantages are enabled in marine systems as a result of improved time stability. Preserving synchronization of assets improves communications, navigation, and ranging. Similar to the benefits to ground-based GPS systems, the CSAC can enable longer periods of autonomous operation and reduced time at surface to reacquire GPS position.

A benchtop demonstration is planned to validate the CSAC impacts to a GPS system. These will involve interfacing the CSAC frequency standard to an RCI DAGR (Defense Advanced GPS Receiver). Experiments will measure time to first fix vs. Time Since Last Track both with the CSAC time base as well as without CSAC time base (i.e., using the internal frequency standard in the existing DAGR). The DAGR presently has two frequency standard interfaces: external synchronization through 1 PPS input and an internal 10.949297 MHz Temperature Sensing Crystal Oscillator. Thus, for the insertion demo we will use the CSAC as an external 1 PPS synchronization source and use a 10.949297 MHz crystal (VCXO) within CSAC as the internal time source for DAGR.

CONCLUSIONS

The CSAC technology offers a valuable capability for precision time/frequency stability in a compact, low-power form. Previous efforts have validated the ability to achieve significant reductions in size and power while retaining excellent frequency stability. Present efforts addressing mechanical and environmental robustness will represent key steps to exploiting this capability in operational environments. An initial assessment of potential system impacts suggests the CSAC could offer

significant performance benefits across a wide spectrum of system applications.

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REFERENCES

Beard, R.L., "Military Time/Frequency use of Navstar GPS," IEE Colloquium on Precise Time and Frequency - the Beat of a Single Drum, 11 Nov 1992 Page(s):5/1 - 5/4

DeNatale,J.F., Borwick, R.L., Tsai, C., Stupar, P.A., Lin, Y., Newgard, R.A., Berquist, R.W., and Zhu, M. "Compact, Low-Power Chip-Scale Atomic Clock," Proc. IEEE ION/PLANS 2008, Monterey, CA USA May 5-8, 2008

Kenyon, Henry S. "Small Atomic Clocks Chart New Horizons." SIGNAL Magazine, April 2008;

Kitching, J., Hollberg, L., Knappe, S., and Wynands, R., "Compact atomic clock based on coherent population trapping," Electronics Letters, Vol. 37, No. 24, Nov. 22, 2001, pp. 1449-1451

Kitching, J., Knappe, S., Liew, L., Schwindt, P. D. D., Gerginov, V, Shah, V., Moreland, J., Brannon, A., Breitbarth, J., Popovic, Z., and Hollberg, L. "Chip-scale atomic frequency references," ION-GNSS 18th International Technical Meeting of the Satellite Division, 13-16 September 2005, Long Beach, CA, pp1662-1669

Laws, A.D., et al., "Thermal and Structural Analysis of a Suspended Physics Package for a Chip-Scale Atomic Clock," Proceedings of ASME InterPACK '07 , July 8-12, 2007, Vancouver, British Columbia, CANADA

Lutwak, R., et al., "The chip-scale atomic clock – prototype evaluation," Proceedings 39th Annual Precise Time and Time Interval (PTTI) Meeting, November 26 - 29, 2007, Long Beach, CA, pp269-290

Rollo, Randy "Navigation Nugget: new chip-scale atomic clock plus GPS receiver transforms navigation." CHIPS, April-June 2007 (http://www.chips.navy.mil/archives/07_Jun/PDF/Navigation_Nugget.pdf)

Stahler, M., Wynands, R., Knappe, S., Kitching, J., Hollberg, L., Taichenachev, A. and Yudin, V., "Coherent population trapping resonances in thermal 85Rb vapor: D1 vs. D2 line excitation," Optics Letters, vol. 27, No. 16, Aug. 15, 2002, pp. 1472-1474